Observations on the Practice of Installing Vibrating Wire Piezometers on Slope Inclinometer Casings

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ABSTRACT
Water Security Agency (WSA) owns and operates 72 water dams throughout the province of Saskatchewan. Geotechnical instrumentation is a key component in understanding the performance of these structures. Slope inclinometers (SI) and vibrating wire piezometers (VWP) are the two most common instruments used in monitoring dams. While fully grouted installations of diaphragm piezometers were first suggested by Vaughn in 1969, wide adoption of the fully grouted method has occurred largely within the past two decades. In general, practitioners are attracted to the method as it provides the ability to install VWPs in the same borehole as a SI casing, providing substantial savings to clients and owners. Regardless of the popularity of the method, and the attractiveness of the cost savings, the effectiveness of such installations should be interrogated to ensure accuracy of monitoring data is suitable. As the owner of extreme consequence dams, WSA is required to monitor instruments year-round. Due to severe winter temperatures and to prevent freezing, the water in the SI casings is pumped below frost elevation prior to winter to ensure monitoring is not disrupted. Observations during pumping indicated that the removal of water from the SI casings had significant impacts on VWPs that were attached to the casings. This paper explores the influence of the water column within the SI casing on the attached VWPs. Numerous installations at two major Saskatchewan dams were studied to provide evidence of the influence of standing water in SI casing on VWPs.

RÉSUMÉ
Water Security Agency (WSA) possède 72 barrages situés à travers la province de la Saskatchewan. Un aspect clé de la compréhension des performances géotechniques de ces structures est l'utilisation de l'instrumentation. Les inclinomètres de pente (SI) et les piézomètres à fil vibrant (VWP) sont les deux instruments les plus couramment utilisés dans la surveillance et l'entretien des barrages. Alors que les installations entièrement jointoyées ont été suggérées pour la première fois par Vaughn en 1969, une large adoption de la méthode d'installation entièrement coulée pour les piézomètres à membrane s'est produite en grande partie au cours des deux dernières décennies. En général, les praticiens sont attirés par la méthode car elle offre la capacité et l'efficacité d'installer des VWP dans le même trou de forage que le tubage SI, ce qui permet des économies substantielles aux clients et aux propriétaires. Compte tenu de la popularité de la méthode d'installation et de l'attrait des économies de coûts, l'efficacité de telles installations doit être envisagée pour garantir que l'exactitude des données de surveillance est maintenue. En tant que propriétaire de barrages à conséquences extrêmes, WSA est tenue de surveiller les instruments toute l'année. En raison des températures hivernales rigoureuses et pour éviter le gel, les carters SI sont pompés avant l'hiver pour s'assurer qu'ils peuvent être surveillés. Les observations pendant le pompage ont indiqué des impacts significatifs sur les données de surveillance des VWP qui étaient attachés aux tubages SI. Cet article explore l'influence de la colonne d'eau dans le boîtier SI sur les lectures du VWP joint. Un certain nombre de ces installations à deux grands barrages de la Saskatchewan ont été étudiées pour fournir des preuves de l'influence de l'eau stagnante dans les conduites SI sur les VWP.

1 INTRODUCTION

Instrumentation is a critical element to the effective performance monitoring of embankments and slopes. Key instrumentation used in performance monitoring includes a combination of slope inclinometers (SI) and piezometers. Given their frequency of use, growing popularity of the fully grouted installation method (FGM), and potential cost-savings associated with combined installations, slope inclinometers and vibrating wire piezometers (VWP) are often installed in the same borehole.

Field observations from six instrumented boreholes at two Water Security Agency (WSA) dams (Duncairn Dam and Grant Devine Dam) have been compiled. Both dams are located in southern Saskatchewan and are classified as Extreme consequence based on CDA guidelines. Duncairn Dam is located on Swift Current Creek and is approximately 30 km south-west of the City of Swift Current. Grant Devine Dam (formerly Alameda Dam) is located in the south-east corner of the province on Moose Mountain Creek approximately 4 km east of the Town of Alameda.

WSA owns 72 dams across the province of Saskatchewan. Geotechnical instrumentation is one facet of WSA's monitoring program. Extreme Consequence dams require year-round monitoring. In Saskatchewan, this schedule demands consideration due to frozen conditions. In the winter of 2020/2021 air temperatures at Duncairn Dam and Grant Devine Dam reached lows of -35.8 and -36.9 degrees Celsius, respectively. Both dams have weather stations with temperature records on site, these records for December 2020 through March 2021 are provided in Figure 2. These seasonal temperatures indicate the majority of days are below freezing for a three-month period, consistent with climate expectations for the region. Due to this, water in SIs needs to be pumped prior to winter to ensure monitoring efforts are not obstructed by ice in the casings. Lowering the water level in SIs prevents freezing and allows for data collection.

Observations during the pumping of the SIs indicated that there were significant impacts on the VWPs attached to the SI casings when the water level was rapidly reduced.

Figure 1. Location of Duncairn Dam and Grant Devine Dam (modified from ESRI, 2021)

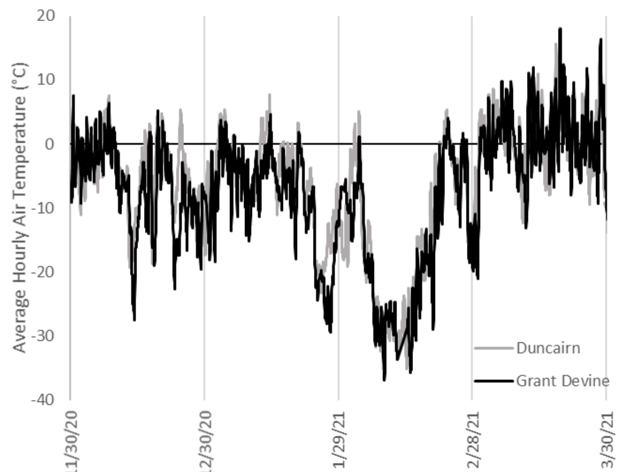

Figure 2. Temperature plot from Duncairn Dam and Grant Devine Dam weather stations for winter 2020/2021.

2 SITE BACKGROUND

2.1 Duncairn Dam

Duncairn Dam impounds Swift Current Creek approximately 30 km upstream of The City of Swift Current and was constructed as a zoned earthfill embankment by the Prairie Farm Rehabilitation Administration (PFRA) in 1942. WSA assumed ownership in the recent dam transfer from Agriculture and Agri-Foods Canada (AAFC). Duncairn Dam was constructed to provide a source of water for multiple irrigation projects, supply water to the City of Swift Current, and for recreation purposes. The dam continues to provide water supply for rural users and provides some flood control measures for the downstream stakeholders.

Swift Current Creek occupies a Pleistocene meltwater channel, and Duncairn Dam stands approximately 20.4 m high within the channel. Stratigraphy at the site of Duncairn Dam can be generalized into four units: embankment fill, downstream berm gravel fill, alluvial clays, silts and sands, and clay shale. It is reasonable to assume, given period the dam was constructed in, that the embankment fill is a variable clay fill. The regional stratigraphy generally consists of an undulating moraine of the Wymark Till Formation (Christiansen,1959). The Wymark Till is generally 3 to 5 m in depth and is underlain by Tertiary Cypress Hills Formation and the Upper Cretaceous Bearpaw Formation. The Cypress Hills Formation is granular in nature, and is composed of well-rounded pebbles and cobbles, and may be locally cemented to form a conglomerate (Christiansen, 1959). The slope wash seen along the reservoir demonstrates the nature of this unit, with the cobbles from the unit providing natural erosion protection along te shores. While cobbles are a dominant feature, the unit can also consist of largely sandy or clayey materials. Meanwhile the Bearpaw Formation is a famously challenging foundation formation, contributing to several geotechnical challenges in the prairies. Notably, the challenges in construction, operation, and maintenance that the Bearpaw Formation has caused at the South Saskatchewan River Project (Peterson, 1954; Jaspar and Peters, 1979). It should be noted that the Bearpaw Formation is the controlling factor of slumping within the

Swift Current Creek area, particularly in areas where the creek has down-cut into the formation (Christiansen, 1959). Bearpaw shale, similar to other shales found on the prairies, is a low permeability unit with hydraulic conductivities on the order of 10^{-11} to 10^{-13} m/s (Peterson, 1954).

The instruments used in this study are shown in Figure 3.

Figure 3. Duncairn Dam layout and instrument locations (modified from Google Earth, 2021).

2.2 Grant Devine Dam

Grant Devine Dam impounds Moose Mountain Creek to form the Grant Devine Reservoir approximately 4 km East of the Town of Alameda. The 42 m high zoned earthfill embankment was constructed between 1991 and 1995 by the Souris Basin Development Authority and is now owned and operated by WSA. Grant Devine Dam provides flood protection, local drinking water, recreation, and is a source of irrigation during drought years. Features included in the embankment include a chimney drain, downstream drainage blanket, six relief wells installed in bedrock along the downstream berm which was added to the embankment due to displacements encountered during construction.

Moose Mountain Creek is located along the north eastern edge of the Weyburn Plain, separating the plain from Moose Mountain and the Missouri Coteau (Christiansen, 1956). Moose Mountain Creek occupies the meltwater channel that drained Glacial Lake Arcola during the last glaciation (Christiansen, 1956). Regionally, the melt water channel dominates the topography, while there are outwash plains within the channel and undulating morainal features otherwise present. The general site stratigraphy at Grant Devine Dam includes alluvial deposits, glacial till, and Ravenscrag Formation bedrock. The alluvial deposits are noted as silt and silty gravel. It was high porewater pressures within the till and shale units that caused large displacements during construction. Dr. Karl Sauer noted a variety of tills within the vicinity of the dam including Battleford, Floral, and Warman Formations (nd).

Instrumentation at three boreholes at Grant Devine Dam were tested. The location of these test locations is provided in Figure 4.

Figure 4. Grant Devine Dam layout and instrument locations (modified from Google Earth, 2021).

3 LITERATURE REVIEW

3.1 Piezometers

Standpipe, pneumatic, and Casagrande style piezometers have fallen by the wayside with the increasing popularity of vibrating wire piezometers (VWP) for monitoring pore water pressure in dams. Current data logging capabilities, with telemetry and the ability to collect a continuous data record have made VWPs appealing to most users despite the increased costs associated with the technologies. VWPs measure water pressure with a diaphragm attached to a vibrating wire sensor.

Piezometers have long been a tool employed for field measurements of porewater pressures, with beginnings in the 1940’s and 1950’s (Cooling, 1951; Penman, 1956). Terzaghi defined effective stress in the 1930’s, and it is without a doubt that porewater pressure plays a significant role in the stability of slopes (Terzaghi et al. 1996; Terzaghi, 1936). It is believed that diaphragm style field piezometer apparatuses were developed and employed in the United Kingdom and the United States of America during the construction of several dams in the middle of the 20th century with development driven by Building Research Station and United States Bureau of Reclamation (USBR) respectively (Cooling, 1951; Penman, 1956). Prior to this the technology was limited to open standpipe (Casagrande) style piezometers, or wells drilled, excavated, or bored for the observation of groundwater. Diaphragm type piezometers also had the benefit of rapid response to porewater pressure changes within clays (Penman, 1961), and the option to install multiple monitoring points within one borehole.

3.2 Fully Grouted Installation Method

The fully grouted installation method (FGM) is an alternative to conventional sand pack installations. Installing VWPs with the sand pack method requires significant skill as there is risk that sand or bentonite pellets will bridge or cave in the installation (McKenna, 1995). This challenge is eliminated by the FGM, along with providing and opportunity to install in deep or non-vertical boreholes.

Use of grout for the installation of diaphragm piezometers gained support as early as 1969 with Vaughan's paper. Despite this early support, and the benefits that FGM provides, the sand pack method was the preferred approach of most practitioners into the 21st Century (Mikkelsen, 2002; Yungwirth et al. 2013). A major driver of the adoption of the FGM may be attributed to McKenna's 1995 paper on such installations in the oilsands.

Despite recent widespread adoption of the FGM there is no ASTM standard method for its use and the reliability of measurements from fully grouted piezometers are still questioned (Marefat et al., 2019). Several potential sources of error were identified by Smerdon et al. (2014) including:

- Leakage or short-circuiting through preferential pathways within the grout;
- High contrast in hydraulic properties between the formations and grout; and,
- Degradation of the grout due to thermal or chemical effects.

3.3 Grout and Hydraulic Conductivity

Grout is a key element in the FGM and ensuring it can achieve the expected performance is necessary in successful installations. One challenge that the FGM faces, is that in some geologic settings, a grout mix that has a lower permeability than all formations is not possible, particularly in the clay rich tills and shales found on the Prairies. The high volumes of bentonite required to achieve low permeability grout also cause the grout to become viscous, difficult to pump, and unable to flow easily around obstructions. Prior to utilizing the FGM it should be confirmed that the following two conditions can be met:

- The grout is less permeable than the least permeable formation (Vaughan, 1969; McKenna, 1995); and,
- The grout is no more than three orders of magnitude greater than the permeability of the surrounding ground (Contreras et al., 2008).

While these two conditions are theoretically possible, it is often limited by practical application. Vaughan proposed in 1973 that the maximum permeability of a cement-bentonite grout mix that was able to be pumped was in the order of $5e^{-8}$ m/s.

4 METHODOLOGY

A field investigation was carried out by pumping water out of the SIs, and monitoring VWPs in response to the pumping. The following general steps were taken at each borehole:

- Interval of VWP data logging was decreased (15 to 60 seconds);
- Water level within the SI casing was measured using a water level tape;
- Pump was lowered into the SI and turned on once lowered;
- Pumping until the water level was lowered to the level of the pump (approximately 30 m);
- The pump was removed;
- Water levels in the SIs were monitored for a period of one to three hours using a water level tape; and,
- Data was collected from VWPs and intervals reset to normal monitoring schedule.

A schematic of the testing set up can be found in Figure 5. A submersible proactive pump powered by a battery and connected to half inch tubing was used to rapidly remove the water from the upper ~30m of SI casing.

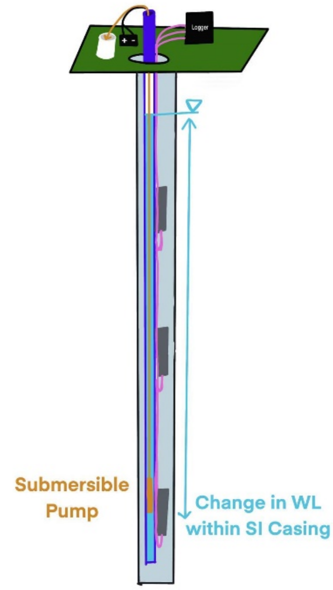

Figure 5. Field testing setup (Nixon, 2021).

Field testing was carried out at Duncairn Dam on August 14, 2019 and Grant Devine Dam on October 8, 2019. Established instrumentation at both sites was selected to ensure an extended record of piezometric data for each instrument was available, grout was set and fully saturated, and pore pressure changes induced by drilling had dissipated. Two boreholes at Duncairn Dam were identified as having VWPs attached to SI, and three boreholes at Grant Devine Dam with a similar configuration.

5 OBSERVATIONS

Pumping was carried out at five installation locations, all of which illustrated minimal rebound in water levels following the conclusion of pumping. SI I-141 experienced the only significant recharge over the test period with approximately 4.3 m. This recharge indicates there is a direct path for water entry into this SI. A summary of the instruments and the observed water levels in SI casings are provided in Table 1.

Table 1. Instrumentation Summary

Dam Inclinometer	VWP	Tip Depth (mbgs)	Depth to Water in SI Before (m)	Depth to Water in SI After (m)
Duncairn I2920	P2921A	26.52	3.970	31.143
	P2922A	12.19		
	P2923A	8.23		
Duncairn I4020	P4021A	22.25	1.045	31.135
	P4022A	10.06		
	P4023A	4.57		
Grant Devine I-141	V-1403	49.08	0.770	16.990
	V-1402	26.25		
	V-1401	16.25		
Grant Devine I-73	V-704A	50	8.580	27.020
	V-708A	41.1		
	V-712A	33.2		
	V-714A	18.6		
Grant Devine I-63	V-610A	50	8.25	27.175
	V-611A	46		
	V-612A	33.8		
	V-604A	18.3		

Figures 6 to 10 show the responses to pumping that were observed in the VWPs attached to the SIs. For I2920A, only the lower piezometer demonstrated a response to the pumping, with a drawdown of approximately 0.662 m observed, shown in Figure 6. The piezometer, P2921A, that demonstrated a response is installed in the Bearpaw Shale formation at Duncairn Dam. It is possible the other two VWPs did not demonstrate a response due to the water column within the SI casing being only 3 to 7 m above their installation locations.

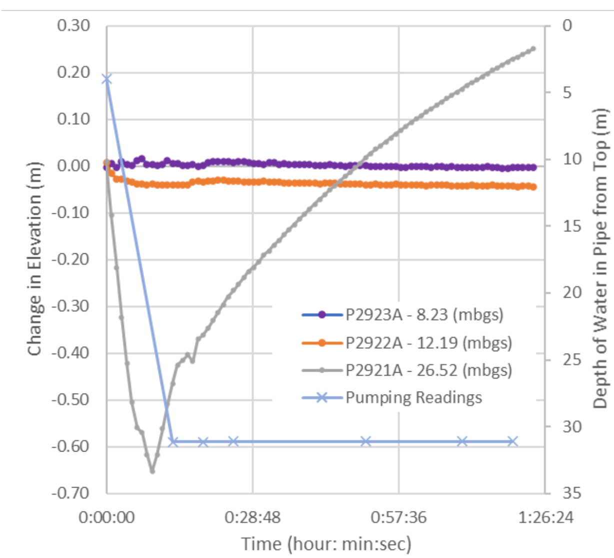

Figure 6. I2920 Vibrating Wire Piezometer Responses to Pumping of the SI Casing

Figure 7 illustrates the response at I4020 and the associated VWPs. Again, at this installation only the VWP within the shale stratigraphic unit, and deepest installation, demonstrated a response to the pumping of the SI casing. It should be noted that the fluid discharged from this casing was cloudy and appeared laden with grout. It is possible that the grout in this installation was not set properly, or that the grout that was observed was a remnant from the time of installation.

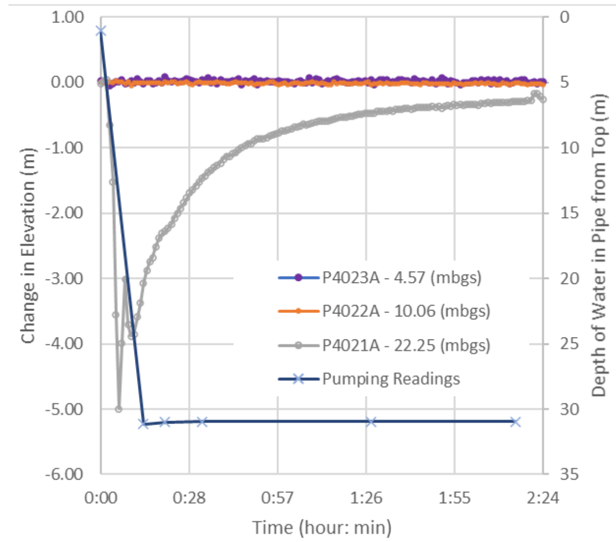

Figure 7. I4020 Vibrating Wire Piezometer Responses to Pumping of the SI Casing

The three boreholes that were included in this investigation at Grant Devine Dam demonstrated responses in VWPs throughout the depth of the borehole, as compared to those at Duncairn where only the deepest VWPs demonstrated a response to the pumping. Figure 8 illustrates that all three VWPs installed on I-141 responded to pumping. This instrument was also the only SI casing that had any significant recharge observed. The deepest piezometer, V-1403, demonstrated the greatest response with 1.824 m of drawdown. V-1403 is installed in a sandstone unit.

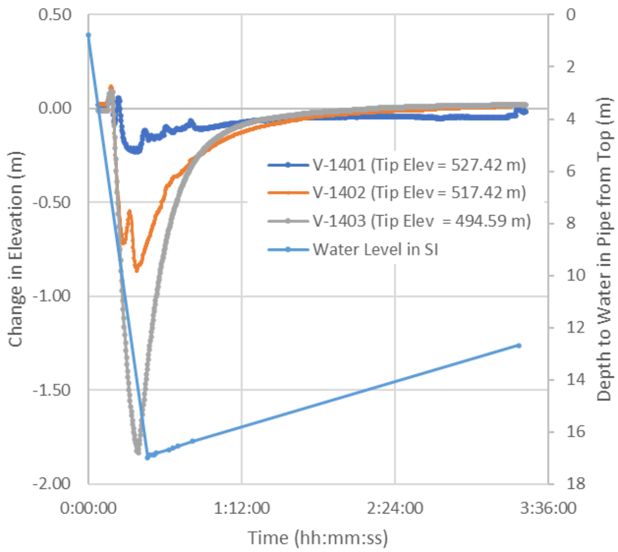

Figure 8. I-141 Vibrating Wire Piezometer Responses to Pumping of the SI Casing

In Figure 9, it is shown that all VWPs installed on I-73 demonstrate a response to the pumping. However, it should be noted that in the uppermost installation, V-714A, the response to pumping is largely noise like response during pumping. This response may indicate that it is not hydraulically connected like the other VWPs, but rather was responding to vibrations caused during pumping. I-73 and I-63, shown in Figure 10 both demonstrate a slower rebound response following the conclusion of pumping. Again, the maximum drawdown for I-73 was observed in V-704A, the deepest VWP installed in shale with a drawdown of 2.72 m observed.

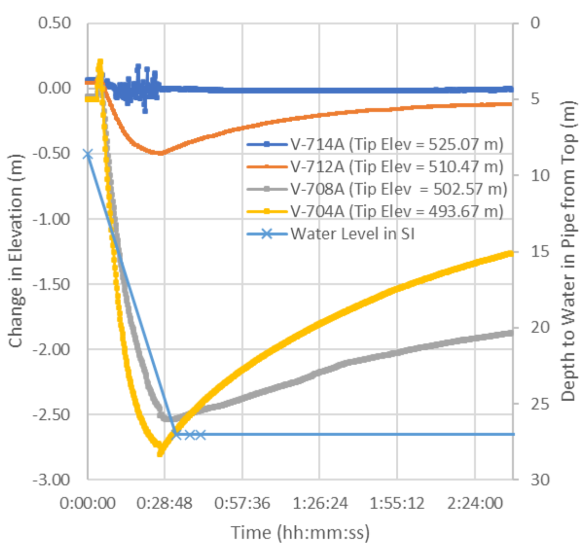

Figure 9. I-73 Vibrating Wire Piezometer Responses to Pumping of the SI Casing

The testing observations for I-63 are shown in Figure 10. These observations once again demonstrate that all VWPs responded to the removal of water from the SI casing. Contrary to the other boreholes involved in the testing, V-612A installed in till, demonstrated the greatest magnitude of response with 1.498 m. This is unique in that it was not the deepest installation within the borehole.

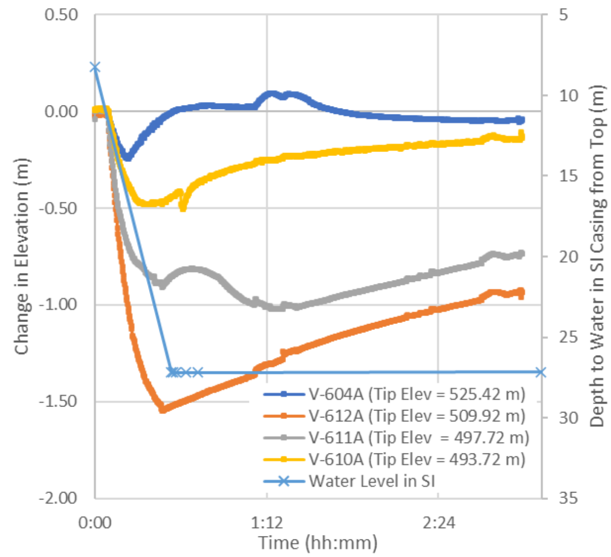

Figure 10. I-63 Vibrating Wire Piezometer Responses to Pumping of the SI Casing

Overall, it is apparent that VWPs installed on the outside of SI casings using the FGM are impacted by the removal of water from the SI. The majority of the tests also indicated that there is some correlation between depth of the VWP and the magnitude of drawdown in the VWP measurements observed. Figure 11 illustrates these increasing drawdown observations with increasing depth trend, with one outlier. This outlier, P4021A, also was the VWP that indicated the greatest magnitude of drawdown during testing. It is possible that this outlying value has been caused from improperly set grout, as the discharge from the pumping of this borehole appeared installation did not have properly set grout, as observed from the discharge during pumping. In removing the outlying value it is observed that there is an increasing drawdown observed with increasing depth of VWP following the removal of the water column within the SI casing, as shown in Figure 12.

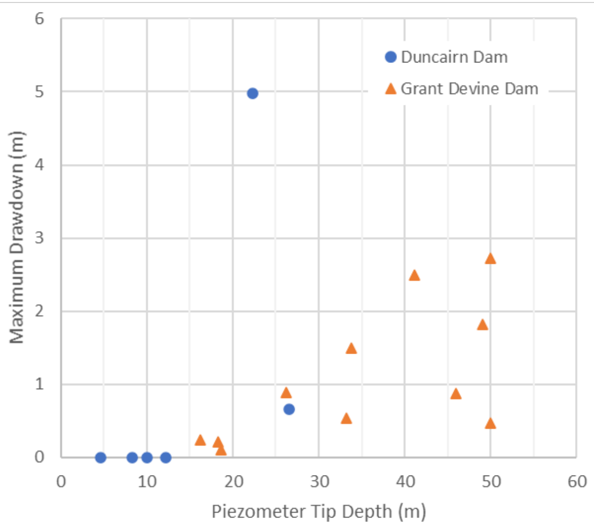

Figure 11. Tip Depth versus Maximum Observed Drawdown

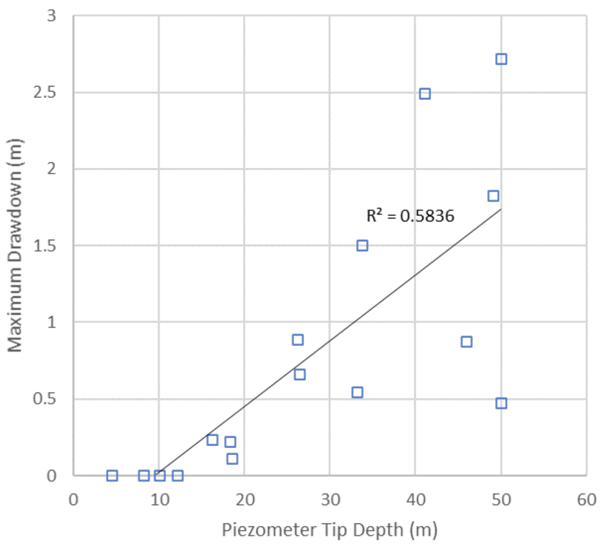

Figure 12. Tip Depth versus Maximum Observed Drawdown Excluding Outlier

Comparison of the drawdown and VWP tip depth indicate that VWPs that were less than 15 m below ground surface demonstrated a negligible response to the pumping. It is possible that this increasing drawdown with depth indicates the condition of SI joints below 15 m are in poorer condition leading to leakage and hydraulic connection, or that the responses are influenced by a change in the radial pressure exerted by the water column on the SI casing.

6 CONCLUSIONS

This paper provides a clear indication that VWPs installed on SI casing demonstrate a hydraulic connection to the water pressure within the SI casing. For WSA, and other owners who monitor instrumentation year-round and complete pumping of the SI casing to do so, this provides evidence that pumping of the SI leads to a response in VWP measurements. It is however, promising to note that most VWP measurements rebounded within a couple of hours and therefore impacts of removing water from the casing may be time-limited. Records of pumping for winter access should be created, and VWP readings taken near the pumping time should be considered invalid. This paper also questions the viability of the FGM and indicates the need for clear industry installation standards to be developed. Overall, the use of the fully grouted installation method and the installation of VWPs on the outside of SI casing appears to create erroneous conditions for the measurements taken by VWPs in such installations. Recommendations for future work include:

- Conduct field testing on dual VWP/SI installations with multiple piezometers within the same stratigraphic unit;
- Simulate the relaxation of the SI casing with the removal of the water column using a numerical model; and,
- Simulate leakage from SI casing joints within a numerical model.

This study has indicated that the pumping of SI casings in preparation for winter does impact VWP readings. As pumping the SI casings is required to ensure access to the SIs for winter monitoring, WSA will continue the practice but begin keeping record of the pumping. These records will be used to ensure any VWP readings during the impacted day are marked invalid. While this will be carried out for instrumentation already installed together, WSA will discontinue the practice of installing VWPs on SI casing going forward. A separate, adjacent, borehole will be utilized where both instruments are required. As a final result of this study, WSA will be working towards the creation of an internal standard for SI and VWP installations, including grouting recommendations. To do so, WSA will be conducting a grout study that includes local supplies to reduce variables.

7 ACKNOWLEDGEMENTS

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